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Published in:
Proceedings of 2013 Conference on Lasers and Electro-Optics (CLEO)

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Rishøj, L. S., Ramachandran, S., & Rottwitt, K. (2013). Intermodal Raman Scattering between Full Vectorial Modes in Few Moded Fiber. In *Proceedings of 2013 Conference on Lasers and Electro-Optics (CLEO)* (pp. CTu3K.2). IEEE.

Intermodal Raman Scattering between Full Vectorial Modes in Few Moded Fiber

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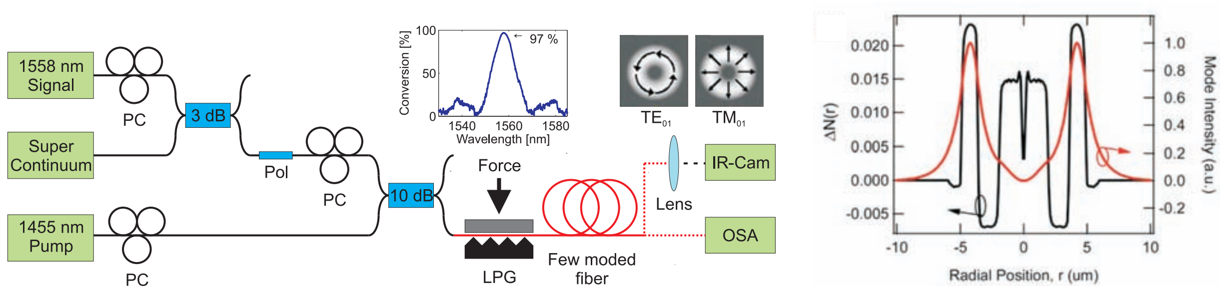
Abstract: We experimentally investigate intermodal Raman interaction. The pump is in the fundamental mode, HE_{11}, and the signal is in either of two full vectorial modes, TM_{01} or TE_{01}. The on-off gain is approximately 3 dB for both modes, using 4 km of few-moded fiber and 400 mW of pump power.

OCIS codes: 190.4370 (Nonlinear optics, fibers); 190.5650 (Raman effect).

Over recent years intermodal Raman scattering has received increasing attention. The interaction between linear polarized psedomodes in a hollow-core photonic crystal fiber (PCF) was studied in [1]. Previously, spontaneous Raman scattering was utilized in the fiber used in this paper to generate vortex beams over a broad wavelength range by pumping at 1064 nm [2]. Furthermore, spacial division multiplexing (SDM) has been proposed as a mean to expand the optical communication bandwidth, either using multi-core fibers (MCFs) or few-moded fibers (FMFs). For long-haul communication optical amplification is crucial, in this regard FMFs has the advantage of intensity overlap between the different modes, which enables sharing of a single pump between multiple signal modes [3]. In this paper measurements of intermodal Raman scattering is presented for a 4 km specialty designed fiber [4]. The pump is in the fundamental mode, HE_{11}, whereas the signal is in HE_{11} or either of the two full vectorial modes, TM_{01} or TE_{01}.

The schematics of the experimental setup is provided in Fig. 1a. The mode excitation is performed using a long



(a) (b)

Fig. 1: (a) Schematics of the experimental setup. (b) Index profile (black) for few moded fiber, and the radial intensity profile for TE_{01} (red).

period microbend grating (LPG). The grating is created by pressing an aluminium block with periodic grooves and a rubber pad together. The supercontinuum source is used to optimize the mode coupling by adjusting the polarization controller (PC) after the polarizer (pol) and the pressure on the fiber. Insets are provided of the two modes of interest, where the arrows indicate the polarization of the mode. The inserted graph shows a typical conversion spectrum; in this example the maximum conversion from HE_{11} to TE_{01} is approximately 97 %. After the seed signal at 1558 nm, the pump at 1455 nm, and the supercontinuum source are combined the FMF (red) is spliced to the SMF (black). The output of the FMF is either measured with an OSA or imaged on an IR-camera. The index profile of the FMF is seen in Fig. 1b. The fiber design eliminates the degeneracy of the first mode group consisting of TM_{01} (radially polarized), TE_{01} (azimuthally polarized), and the two degenerated modes HE_{21} (mixed polarized). Therefore strong mode coupling between this first mode group yielding the familiar LP_{11} mode is avoided, and controlled excitation of the individual full vectorial modes is ensured, together with stable propagation along the fiber [4]. The loss for HE_{11} was measured at 1.4 dB/km, whereas for TM_{01} and TE_{01} it was 1.6 dB/km. The rather high loss is a consequence of the large index steps in the fiber design, which are needed to eliminate the degeneracy.

The on-off Raman gain as a function of pump power is shown in Fig. 2a. The pump is in the fundamental mode, HE_{11}, whereas the signal is in either HE_{11}, TM_{01}, or TE_{01} as indicated by the legend. Each measurement is carried out over 100 s; an example of a measurement is shown in Fig. 2b (blue line). The fluctuations in power are caused by interference between different modes in the fiber. The fluctuations are significantly smaller for 2 m of FMF (green line); this indicates that the parasitic modes are primarily excited by undesired mode propagation instability over the long length of the fiber. For 2 m of fiber the main contribution is from conversion at the splice point. In Fig. 2a the line denotes the average power and the error-bars indicates one standard deviation. The smaller error-bars for HE_{11} indicate larger mode stability, which is expected since the difference in propagation constant is largest between the fundamental mode and all remaining modes in the fiber. The process of Raman scattering depends primarily on the

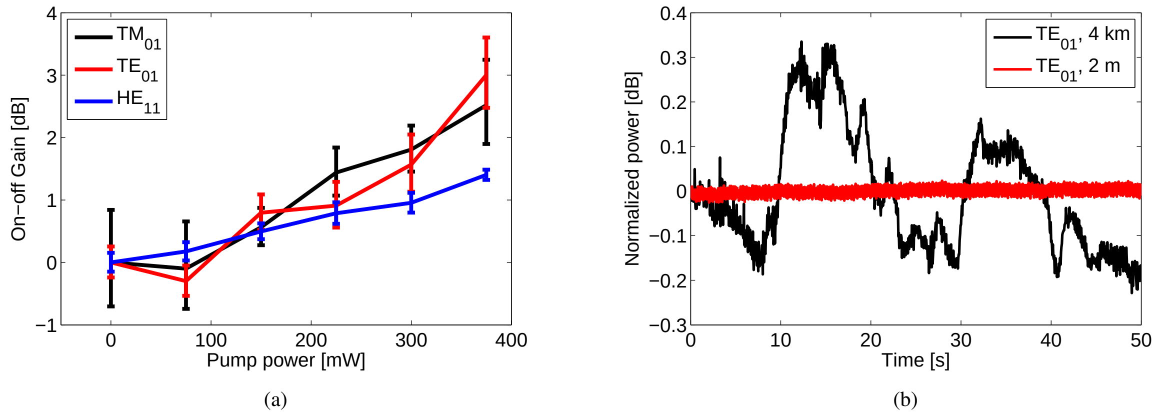


Fig. 2: (a) Intermodal Raman gain as a function of pump power. (b) Power as a function of time for different fiber lengths.

co-polarized intensity overlap integral between the modes. The inverse of this integral yield an effective Raman area, between the fundamental mode at 1455 nm and the TM_{01} and TE_{01} modes at 1558 nm these areas are calculated at 236 μm^2 and 234 μm^2, respectively. Hereby indicating that the Raman gain is similar for these two modes. The TM_{01} and TE_{01} are inherently polarization preserving [4], hence when the signal are in either of these two HOMs the strength of Raman scattering becomes independent of polarization walk-off. The effective Raman area when the signal is in the fundamental mode is 102 μm^2, however due to polarization walk-off the Raman scattering strength is reduced by a factor of two, which means that the gain is expected to be 15 % higher when the signal is in the fundamental mode compared to the HOMs. However, it was observed that the gain was higher for the HOMs, this is expected to be caused by the large germanium concentration in the outer ring of the index profile, see Fig. 1b, since this is known to increase Raman scattering [5].

In summary, the intermodal on-off Raman gain was measured between full vectorial modes in a specialty designed fiber. By pumping in the fundamental mode approximately 3 dB of gain was demonstrated for both TM_{01} and TE_{01} in a 4 km fiber using 400 mW of pump power.

Acknowledgment

The Danish Research Council for Technology and Production Sciences (project 09-066562) is acknowledged for financial support. OFS Fitel Denmark is acknowledged for providing the fiber.

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